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A Parametric Representation of a Thunderstorm Cell

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13. Abstract (Maximum 200 words). The TSTORM feature model, a simple parametric representation of a thunderstorm cell, is described. TSTORM is designed for use in simulations requiring an idealized magnitude and spatial distribution of significant meteorological parameters within a thunderstorm. A full description of the TSTORM algorithm, a test case demonstrating its capabilities, and a computer listing, are provided.					
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A PARAMETRIC REPRESENTATION OF A THUNDERSTORM CELL

1. INTRODUCTION

Rapid advances in computer technology within the last decade have led to dramatic increases in the use of modeling and simulations within all branches of the Department of Defense. Models and simulations now are utilized in many functional areas, including training and military operations, research and development, test and evaluation, and cost analysis. Simulations which deal with atmospheric effects or require environmental data may utilize feature models, which provide simple parametric representations of specific atmospheric features. A feature model may be superimposed on an initial data field to increase atmospheric fidelity or provide time variability, or may be used as a unique environmental source for the simulation.

This report presents a feature model of a thunderstorm cell, the basic constituent of the common multi-celled thunderstorm. Unlike numerical convective models, which describe the development and structure of a thunderstorm using mathematical equations to represent its dynamic and microphysics processes, the feature model described herein (TSTORM) only provides a simplistic representation of thunderstorm structure based on equations which combine elementary algebraic and transcendental functions. While this parametric representation of a thunderstorm is not as physically consistent as a numerical model and does not provide developmental and structural aspects possible with the more complex numerical model (e.g., a storm's life cycle, water phase changes, heat transfers), it does provide ease of use, flexibility and implementation capability on the simulator computer system.

As a data source to a host simulation, the TSTORM algorithm is capable of providing a three dimensional (3-D), steady-state depiction of several meteorological fields within a "typical" mature thunderstorm cell; these fields include the vertical velocity, the total water

content (liquid plus solid), the horizontal wind direction and speed, and the temperature and pressure anomalies relative to the non-storm environment. Electrical activity and lightning within the thunderstorm cell are not modeled. A dropsize distribution based on an empirical relation from Marshall and Palmer (1948) is available at user-specified storm locations. Variations in storm intensity are provided in TSTORM through adjustments in a few initialization parameters. If superimposed on a coarser data field, the time history of a thunderstorm cell may be simulated by propagating TSTORM environmental fields past a selected location.

2. TSTORM DESCRIPTION

2.1 Design Framework

The TSTORM algorithm computes meteorological fields within a 3-D (x,y,z) framework (see Figure 1a). Here, both the x- and y-axes extend over the interval $[-1,1]$, while the vertical axis extends from the ground to the cloud top (H). In TSTORM, the y- and z-coordinates represent distance; the x-coordinate can either represent distance or time. If the x-axis corresponds to distance, then TSTORM provides a 3-D steady-state depiction of a thunderstorm cell; for this representation, the points A and B of Figure 1a would be surface locations on the storm's perimeter while point C would be at the storm's (coordinate) center. On the other hand, if the x-coordinate represents time, a (y,z) vertical slice at any selected value of x on the interval $[-1,1]$ provides an instantaneous representation of the simulated thunderstorm cell structure at a specific time during passage of the cell at a station. The designation of the x-axis as time is possible since TSTORM parameterizations are developed on the assumption that the storm's translational motion (V_T) is along the x-axis. In this case, the points A and B of Figure 1a correspond to pre- and post-storm locations, respectively, while point C corresponds to the time when the storm is directly overhead.

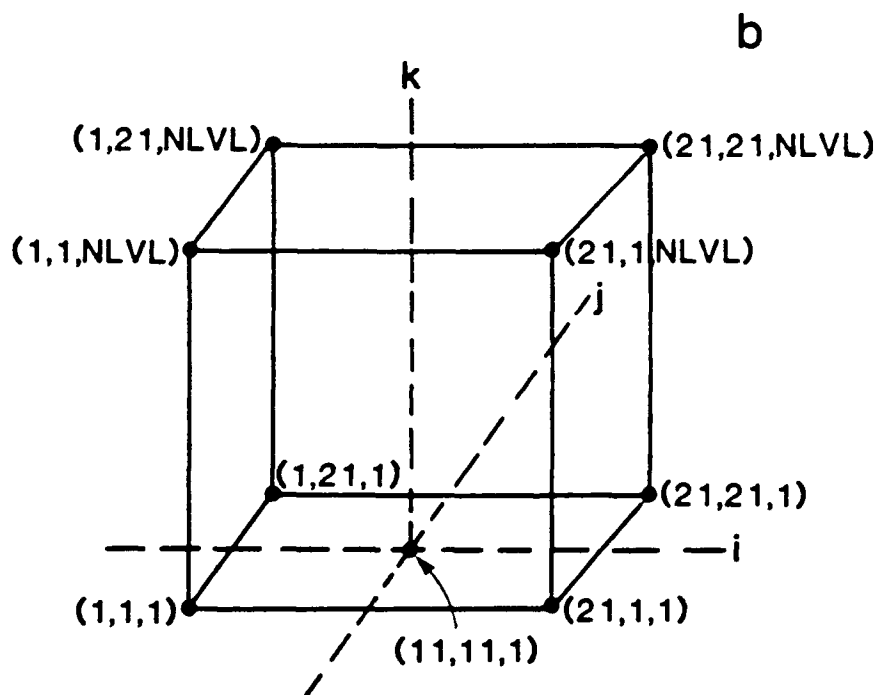
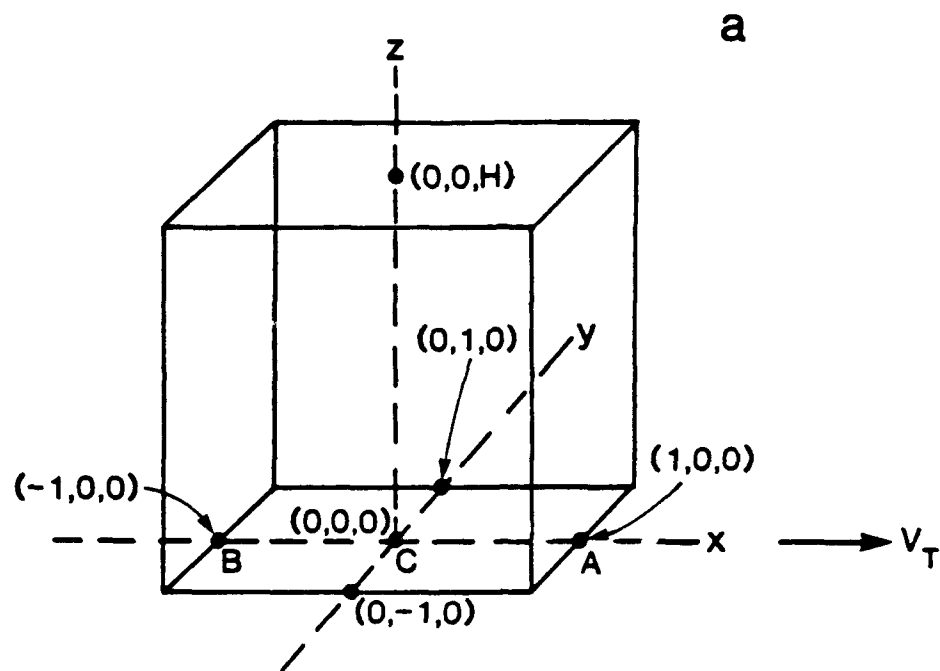


Figure 1. The TSTORM algorithm coordinate system. a) Cartesian (x,y,z) coordinates, b) Grid point (i,j,k) coordinates.

The TSTORM meteorological fields are computed on a 3-D grid (see Figure 1b). Here, both the x- and y-dimensions are set to 21, corresponding to a grid spacing of 0.1 units. The vertical coordinate NLVL (the number of levels) is of variable dimension depending on what value of H is selected ($NLVL = 2 \cdot H + 1$); the TSTORM algorithm presets the vertical grid spacing to 0.5 km.

2.2 Inputs, Outputs, and Limits

With reference to the computer program listing provided in the Appendix, inputs and outputs to the TSTORM subroutine subprogram are executed within the calling program (i.e., the demonstration driver program) by means of the following statement:

```
CALL TSTORM(NLVL,H,WMAX,VMAX,WDSFC,VEER,NLOC,XDSD,YDSD,ZDSD,  
            W,TA,PP,WC,WS,WD,DD,DSD,RR)
```

The input parameters (and their permissible values) which are passed to the TSTORM subroutine and which need to be specified by the operator are:

- 1) Number of levels (NLVL) - 13 to 31
- 2) Thunderstorm height (H) - [6.0,6.5,...14.5,15.0] km
- 3) Storm maximum vertical velocity (WMAX) - 6 to 15 m/s
- 4) Wind speed at level H (VMAX) - 10 to 30 m/s
- 5) Surface wind direction (WDSFC) - 0 to 360 deg
- 6) Wind veer, surface to level H (VEER) - \pm 360 deg
- 7) Number of sites for dropsize distribution (NLOC) - ≥ 1
- 8) Coordinates (x,y,z) for each dropsize distribution site

XDSD(NLOC) - [-1.0,-0.9,...0.9,1.0] units
YDSD(NLOC) - [-1.0,-0.9,...0.9,1.0] units
ZDSD(NLOC) - [0.0,0.5,...4.5,5.0] km

The parameters H and WMAX are very important since they control the shape and intensity of the thunderstorm simulation. Generally, the larger the values of H (storm depth) and WMAX (maximum storm vertical velocity), the more severe the thunderstorm. The range in permissible values for H and WMAX allows the operator to simulate thunderstorm cells of varying intensity, from light to moderate, heavy to severe. Note that TSTORM requires H to be specified as a whole number, or a whole number plus 0.5.

The fourth through sixth input parameters specify the background or environmental (outside storm) wind characteristics. The parameter VMAX is important since it controls the entire environmental wind speed profile, from H to the surface; the higher (lower) the value of VMAX, the higher (lower) the wind speed throughout the vertical column. Meteorologically, wind veer is defined as positive (negative) for wind which rotates clockwise (counterclockwise) with height. For example, a surface wind from the east (90 deg) which veers a positive 135 deg will be a southwesterly wind of 225 deg at top level.

Input parameters seven and eight allow the user to specify any number of thunderstorm locations for dropsize distribution (DSD) data. Since the TSTORM algorithm does not provide for spatial interpolation, these DSD locations must be input in Cartesian (x,y,z) coordinates which correspond exactly to TSTORM grid locations. For example, a distribution location specified as (-0.32,0.18,1.2) would be unacceptable, but (-0.3,0.2,1.0) would be valid. In TSTORM, dropsize distribution is computed using an empirical relation based on "rain" drop measurements. Thus, in order to increase the likelihood that dropsize distributions will be specified for liquid (and not solid) water drops, TSTORM limits DSD locations to below 5 km.

After TSTORM subroutine execution, the following six gridded meteorological fields (dimensioned (21,21,NLVL)) are returned to the demonstration driver program and are available to the operator:

- 1) Vertical velocity W (m/s)
- 2) Temperature anomaly T_a (C)
- 3) Pressure perturbation P_p (mb)
- 4) Total water content WC ($g\ m^{-3}$)
- 5) Wind speed WS (m/s)
- 6) Wind direction WD (deg)

Also returned to the calling program are the drop diameter array DD (containing 21 diameters D from 0 to 5 mm), the distribution of the number of rain drops versus diameter, per millimeter diameter interval and per cubic meter of air (DSD), and the rainfall rate RR (in mm/hr). Both DSD and RR are specified for each dropsize distribution location requested by the operator.

The TSTORM temperature and pressure fields (T_a and P_p) are both specified as in-storm anomalies relative to the background (i.e., outside storm) environment. In order to define an actual temperature (pressure) structure within the thunderstorm, the temperature anomaly (pressure perturbation) field would be added to the environmental temperature (pressure). Although TSTORM does not provide background temperature or pressure, they could be provided by the simulator in the form of actual temperature or pressure vertical profiles. Alternatively, a background temperature profile could be specified by a temperature at a particular height (usually the surface) and an assumed environmental lapse rate (typically 5 to 6.5 C/km). The hypsometric formula, which relates height, temperature and pressure, could then be used to determine the background vertical pressure profile.

In TSTORM, both initialization and output parameters are generally specified in the metric system of units; the algorithm has no capability for conversion from metric to other systems of units (e.g., English). Additionally, the TSTORM algorithm does not provide graphical output displays; these are both user- and machine-dependent and are left to the discretion of the simulator. The demonstration program listed in the Appendix provides the tabular data output of Figures 2 through 7, and 14, of this report.

2.3 Parameterizations

The TSTORM algorithm produces a 3-D structure of significant meteorological parameters within a thunderstorm cell based on combinations of algebraic and transcendental functions. The vertical velocity, the temperature anomaly, the pressure perturbation and the total water content are all initially calculated at grid points of the (x,z) plane above the x-axis (i.e., at y = 0), then expanded horizontally in the y-direction to obtain a full 3-D representation. The horizontal wind speed and direction are computed on the (x,y) plane one level at a time, starting at the surface. The droplet size distribution (DSD) is given by the empirical relation of Marshall and Palmer (1948).

Vertical Velocity W

The 3-D vertical velocity field created by TSTORM is dominated by two mid-level cores - an updraft core in the forward part of the storm, and a downdraft core within the rear sector. For given values of x and z at y = 0, the vertical velocity W(x,0,z) is obtained as the product of the following two equations:

$$W1 = e^{-\pi x^2} * \sin(\pi * XDPL) \quad (1)$$

and

$$W2 = \frac{4WMAX}{H} \left(z - \frac{z^2}{H} \right) * \left(1 + \frac{zx}{H} \right) \quad (2)$$

where

$$XDPL = x - \left(0.432 * \left(\frac{H2 - z}{H2} \right)^3 \right) \quad (3)$$

and $H2 = H/2$.

The curve defined by eq. 1 is distinguished by its sinusoidal shape. At $z = H2$, where $XDPL = x$, eq. 1 provides positive numerical values (i.e., upward motion) for all $x > 0$, and negative values (for downward motion) for $x < 0$. The parameter XDPL (eq. 3) modifies values of x to provide a negative vertical tilt (most pronounced at small and large values of z) to the eq. 1 curve. The parabolic function in eq. 2 was used by Kessler (1969) to represent the variation of vertical velocity with height; this function yields a maximum value at mid-level ($H/2$) and values of zero at both the surface and top. When this function is multiplied by eq. 1, the desired two lobe, mid-level structure for W is obtained. The second factor of eq. 2 is used to adjust the positive W lobe slightly upward, and the negative W lobe, slightly downward.

The full 3-D representation of the vertical velocity is given by

$$W(x,y,z) = W(x,0,z) * YFAC \quad (4)$$

where

$$YFAC = (1 - |y|)^2 \quad \text{for } y = [-1,1] \quad (5)$$

The function YFAC provides exponential decreases in vertical velocity values away from the x -axis, for both positive and negative y values.

Temperature Anomaly T_a

The TSTORM 3-D depiction of the temperature anomaly field is dominated by two opposing cores - a warm core located aloft below the updraft maximum, and a stronger cold core which expands and strengthens toward the surface. For given values of x and y at $y = 0$, the temperature anomaly $T_a(x, 0, z)$ is determined by the product of eq. 1 and the following two equations:

$$T1 = e^{-\pi x^2} * (0.3/H2) * (H-z)^2 \quad (6)$$

and

$$T2 = 1 + \{(z^2 * |x|) / (H^2 / 24)\} \quad (7)$$

Additionally, for a $(x, 0, z)$ grid point located within the rear lower sector of the storm (i.e., $x \leq 0$ and $z \leq H2$), the above resultant product is multiplied by

$$T3 = e^x * x * \left(4.32 * \left(\frac{H2-z}{H2} \right)^3 \right) \quad (8)$$

Identical to the vertical velocity parameterization, the temperature anomaly computation starts with the sinusoidal curve of negative vertical tilt defined by eq. 1. An important component of the T_a computation is eq. 6, which provides large numerical values to the computation near the surface near $x = 0$, and zero values (at all x) at the top ($z = H$). Equation 7 is included in the T_a computation to adjust unreasonably low numerical values at large z and at values of x well removed from the z -axis. Another adjustment factor, eq. 8, is included in the computation to insure that negative temperature anomaly values of significant magnitude occur near the surface for all $x < 0$.

Analogous to the vertical velocity, the 3-D representation of the temperature anomaly is given as

$$T_a(x,y,z) = T_a(x,0,z) * YFAC, \quad (9)$$

where YFAC is the exponential function defined by eq. 5.

Pressure perturbation P_p

In a dynamic sense, the pressure perturbation field within a thunderstorm is linked to both the vertical velocity and temperature anomaly fields. In TSTORM, these two fields are used to create a pressure perturbation field characterized by two opposing lobes at mid-storm level, and a positive anomaly at the surface, below the downdraft. For given values of x and z at $y = 0$, the pressure perturbation is computed as

$$P_p(x,0,z) = 0.1 * \{W(x,0,z) - T_a(x,0,z)\} \quad (10)$$

for $z \leq HB$ or $z \geq HT$, and

$$P_p(x,0,z) = 0.1 * \{W(x,0,z) - T_a(x,0,z)\} * \left(z - \frac{z^2}{H}\right) \quad (11)$$

for $z > HB$ and $z < HT$,

where $HB = H/12$ and $HT = H - HB$.

Note that the pressure perturbation disappears at cloud top height H , since both W and T_a are zero. Analogous to the vertical velocity and temperature anomaly, the full 3-D representation of the pressure perturbation is given as

$$P_p(x,y,z) = P_p(x,0,z) * YFAC \quad (12)$$

Total Water Content WC

The parameter WC, which includes liquid and solid water but not water vapor, provides the cloud form as well as the location and intensity of precipitation for the TSTORM simulation. The main features of the WC parameterization include a mid-level core of high water content, a pronounced near-surface "rain" shaft near the storm's center, and a skewness in water content at mid- to upper levels in the direction of storm motion. Mathematically, the water content $WC(x,0,z)$ is initially specified by the addition of the following two equations:

$$WC1 = |T_a(x,0,z)| * (1 - |x|^{1/3}) \quad (13)$$

and

$$WC2 = 2 * \left(z - \frac{z^2}{H} \right) * e^{-\pi \left(x - \frac{.12z}{H^2} \right)^2} \quad (14)$$

The first term WC1 takes the starting value for the water content computation - the corresponding T_a value - and reduces it exponentially outward from the z-axis (i.e., from $x = 0$). The second term WC2 provides large computational values near the z-axis at mid-level heights (i.e., near $H/2$) but small values at large absolute x (i.e., near the periphery); for a given magnitude of x , the last factor of WC2 provides a skewness in x , with larger (smaller) numerical values at positive (negative) x .

For those values of $x \geq 0.4$ or $x < -0.6$ units, $WC(x,0,z)$ is redefined as follows:

$$WC(x,0,z) = 0 \quad \text{for } z \leq HB \quad (15)$$

and

$$WC(x,0,z) = WC(x,0,z) * e^{-x^2} * \left(1 + \frac{zx}{H}\right) \quad \text{for } z > HB \quad (16)$$

Equation 15 is important since it both defines the cloud base in non-precipitating areas (as HB) and sets the horizontal extent of surface precipitation (from $x = 0.4$ to $x = -0.6$ units). The last two factors of eq. 16 are used to further skew $WC(x,0,z)$ in a positive x direction at middle and high levels.

For values of $z \geq H6$ (i.e., $z \geq H/6$), the full 3-D representation for total water content is given as

$$WC(x,y,z) = WC(x,0,z) * YFAC \quad (17)$$

Below $H6$, $WC(x,0,z)$ is multiplied by an additional factor, such that

$$WC(x,y,z) = WC(x,0,z) * YFAC * YFAC^{(H6-z)} \quad (18)$$

The last factor of eq. 18 provides for a more rapid exponential decrease in $WC(x,0,z)$ away from the x -axis (in the y -direction), and results in more circular isopleths of WC on the (x,y) plane at all z below $H6$.

Horizontal Wind WD,WS

Generally, the spatial structure of the horizontal wind field within a thunderstorm is highly complex, varying widely from storm to storm. In spite of this, there are certain wind features that relate to most thunderstorm occurrences which can be easily simulated. These include the strong, divergent surface wind outflow below the storm's downdraft and, at mid-levels, an inner storm structure which differs considerably from that some distance away. For the latter, the TSTORM parameterization assumes that the central core of the storm cell (i.e., the region of strongest up- and downdrafts) offers a formidable resistance to the horizontal wind. Specifically, incoming flow is both diminished and deflected on its approach toward the inner core; once past

this core, winds converge and increase before exiting the storm environment. At high levels near the storm's top, well away from the strong mid-level core, in-cloud winds are relatively unchanged from the outside (environmental) wind.

Given the wind speed at cloud top height H (V_{MAX}), $TSTORM$ defines the environmental wind at any level z as

$$VE(z) = V_{MAX} * e^{\left(-1.68 * \frac{H-z}{H}\right)} \quad (19)$$

For a grid location (x,y,z) , the in-cloud horizontal wind speed (VC) is initially computed as

$$VC = VE * RAD \quad (20)$$

where RAD , the horizontal distance from the storm center $(x_c, 0)$ to the location (x,y) at level z , is defined

$$RAD = \left((x-x_c)^2 + y^2\right)^{1/2} \quad (21)$$

In order to simulate vertical tilt of the storm with respect to the x -axis, the storm's center x -coordinate (x_c) is defined as

$$x_c = \frac{-.16}{H6} z \quad \text{for } z \leq H6, \quad (22)$$

$$x_c = \left(\frac{.16}{H3} * (z-H6)\right) - 0.16 \quad \text{for } z > H6 \text{ and } z < H-H6, \quad (23)$$

and

$$x_c = \left(\frac{.08}{H6} * (H-z)\right) + 0.08 \quad \text{for } z \geq H-H6 \quad (24)$$

where $H3 = H/3$. Both equations (22) and (24) provide negative vertical tilts with respect to x , while eq. 23 provides a positive vertical slope from $z = H6$ to $z = H - H6$.

Given values of VE and VC at the grid location (x,y,z), the in-cloud wind speed VC is redefined to be the smaller of these two values. Here, VC would be reset to VE for all values of RAD greater than one. The wind speed VC is next recomputed in terms of vertical distance from the storm's center (H2), that is,

$$VC = VC + \{(VE - VC) * \frac{1}{H2} * |z - H2|\} \quad (25)$$

The wind speed value given by (25) is the final computational value for all $z > H6$. For levels $z \leq H6$, the strong horizontal wind speeds associated with the cell's downdraft are parameterized as

$$VG = (VC + e^{(H6-z)}) * e^{-\pi RAD} \quad (26)$$

For a grid location (x,y) at or below $z = H6$, the final in-cloud wind speed VC is defined as the larger of VC (from eq. 25) and VG.

Given values of the surface wind direction (WDSFC) and the surface to top wind veer (VEER), the environmental wind direction (WDE) at any level z is defined by

$$WDE(z) = WDSFC + \left(VEER * \sin\left(\frac{\pi z}{2H}\right) \right) \quad (27)$$

In those cases when WDE is computed to be greater than 360 deg (less than 0 deg), a numerical value of 360 is subtracted (added to) the initial value.

At all levels within the thunderstorm cell, the wind direction (WDC) is set equal to WDE provided that the horizontal distance RAD from the location (x,y) to the storm's center ($x_c, 0$), as computed by eq. 21, is greater than or equal to one. At all locations where RAD is less than one, TSTORM parameterizes the wind direction to differ from WDE as an inverse function of

the distance to the storm's inner core. This difference between the background wind direction and the in-cloud direction WDC at a location (x,y,z) is designated the deflection angle ANG.

To determine the deflection angle, the direction vector WDIV from the storm cell's center ($x_c, 0$) to the location (x,y) is first specified as follows:

$$\begin{aligned}
 \text{WDIV} &= 90. & - \arctan(y / x - x_c) & & \text{for } x - x_c < 0 \\
 \text{WDIV} &= 270. & - \arctan(y / x - x_c) & & \text{for } x - x_c > 0 \\
 \text{WDIV} &= 360. & & & \text{for } x - x_c = 0, y < 0 \\
 \text{WDIV} &= 999. & & & \text{for } x - x_c = 0, y = 0 \\
 \text{WDIV} &= 180. & & & \text{for } x - x_c = 0, y > 0
 \end{aligned} \tag{28}$$

For a computed value of WDIV = 999, the corresponding in-cloud wind direction WDC is set to 999. to indicate either no wind (if WS = 0) or a variable wind direction (if WS ≠ 0). Specifying the difference between the background wind (WDE) and the direction vector WDIV as WDIF, the magnitude of the in-cloud wind deflection (in degrees) is initially given as

$$|ANG| = \{ (|WDIF| / 90.) - \text{INT} (|WDIF| / 90.) \} * 90. \tag{29}$$

where "INT" signifies the integer truncation of the specified value. If |ANG| is greater than 45 deg, the magnitude of the deflection angle is redefined as $|ANG| = 90. - |ANG|$. To simulate vertical variation in wind deflection, the magnitude |ANG| is modified as

$$|ANG| = |ANG| * e^{-RAD^2} * \frac{H3}{H} * \left(z - \frac{z^2}{H} \right) \tag{30}$$

The sign of the deflection angle (positive if to the right of the WDE direction vector, negative if toward the left) is computed in terms of the polar coordinates (x', y'), where

$$\begin{aligned}
 x' &= RAD * \cos (WDIF) \\
 \text{and} \quad y' &= RAD * \sin (WDIF)
 \end{aligned} \tag{31}$$

For x' and y' both greater than zero, or both less than zero, the sign of the deflection angle is positive; otherwise, the sign of ANG is negative.

Given the deflection angle ANG, the in-cloud wind direction for a location (x,y) at a horizontal distance RAD less than one unit from the storm's center is simply

$$WDC = WDE + ANG \quad (32)$$

Analogous to equation 27, computed values of WDC greater than 360 deg (less than 0 deg) are brought within permissible range by subtracting (adding) a numerical value of 360 to the initial value.

For the level $z = H6$ and below, the horizontal wind field is parameterized to diverge outward in all directions from the storm center $(x_c, 0)$, provided that the horizontal distance from (x,y) to $(x_c, 0)$ is less than or equal to

$$RADDIV(z) = 0.5 * e^{-z} \quad (33)$$

Here, wind directions at any location (x,y) are specified according to eq. 28 (i.e., $WDC = WDIV$). For horizontal distances greater than RADDIV, but less than one unit, the in-cloud wind direction $WDC(x,y,z)$ at all $z \leq H6$ remains as previously computed by eq. 32.

Dropsiz Distribution DSD

The raindrop size distribution at a user-specified location within the thunderstorm cell is computed according to the negative exponential relation (Marshall and Palmer, 1948)

$$DSD(NLOC, D) = N_0 * e^{-4.1RR^{-0.21}D} \quad (34)$$

where D is the drop diameter, $DSD(NLOC, D)$ represents the number of drops per millimeter diameter interval and per cubic meter of air, N_0 is a constant and RR is the site rainfall rate in mm/hr. The constant N_0 , which corresponds to the value of $DSD(NLOC, D)$ for $D = 0$, is set to $8000 \text{ mm}^{-1} \text{ m}^{-3}$. The dropsiz distribution is calculated for 21 diameters D , from 0 to 5 mm,

in increments of $\delta D = 0.25$ mm. The rainfall rate RR is determined using the empirical relation that the liquid water content of 1 gm^{-3} corresponds approximately to the precipitation intensity of 20 mm/hr (Blanchard, 1953).

3. TEST CASE

In this section, vertical and horizontal cross sections, and raindrop distributions, corresponding to the TSTORM simulation listed in the Appendix, are presented. The physical initialization parameters used for this sample case are as follows:

$$\begin{array}{ll} H = 12 \text{ km} & VMAX = 15 \text{ m/s} \\ WMAX = 9 \text{ m/s} & WDSFC = 90 \text{ deg} \\ & VEER = +180 \text{ deg} \end{array}$$

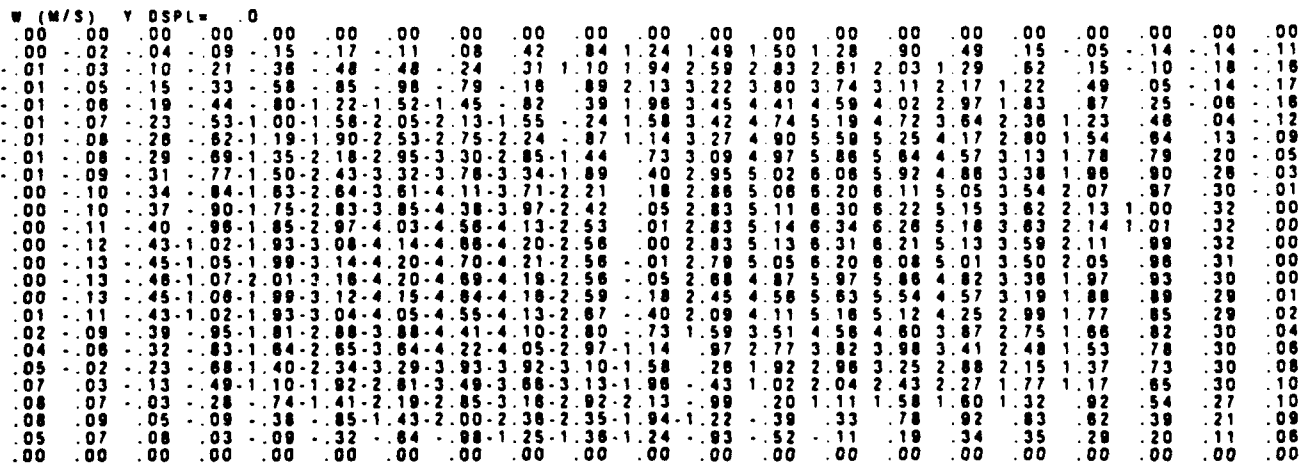
Based on these numerical values, this simulation corresponds to a thunderstorm of a heavy intensity. As for all TSTORM simulations, test case results either represent the structure within an isolated, single-celled thunderstorm or, the structure of one of the several more-or-less independent cells found within the common multi-celled thunderstorm.

In order to interpret test case results in terms of spatial and temporal dimensions, the length of the TSTORM grid's x-axis (from -1 to +1 units) is assumed to correspond to a distance of 20 km and a time of one hour. These values are chosen to agree with observations of Byers and Braham (1949), who determined that a thunderstorm cell of depth $H = 12$ km has a horizontal extent at maturity of about 11 to 12 km, and that the average time duration of rainfall from a single cell of a storm is about a half hour. For a 3-D spatial interpretation of test results (i.e., x corresponds to distance), the interval of $(-0.7 \leq x \leq 0.5)$ would approximately define the spatial structure of the mature thunderstorm cell, with results at $x > 0.5$ and $x < -0.7$ units representing cloudy, non-precipitating areas on the periphery of the storm. Remembering that the storm's translational motion (in this case, 20 km/hr) is assumed by TSTORM to be in the positive

x-direction, the interval from $x = 0.4$ to $x = -0.6$ units (which defines the horizontal extent of surface precipitation) corresponds to exactly a half hour.

3.1 Vertical Cross Sections

At maturity, the vertical velocity structure of a thunderstorm cell is dominated by two separate entities - the updraft and downdraft. The updraft results from the strong entrainment of air at low levels into the thunderstorm on its forward flank, while the downdraft is driven by cold, sinking air associated with the descent of precipitation. Measurements reported by Byers and Braham (1949) indicate updraft speeds mostly in the range 5 - 10 m/s (these averaged over the width of the drafts) with maximum values most common at middle to upper levels and, updraft widths typically 1 to 1.5 km across. The vertical cross section of W for the test simulation (Figure 2) indicates good agreement with these observations, showing the core of the updraft to be at (x, z) coordinates (0.3, 6.5) with a magnitude in excess of 6 m/s over a 1 to 1.5 km wide horizontal distance. The core of the simulated downdraft is found at about 5 to 5.5 km, with a magnitude of 4.7 m/s; these results are in agreement with Byers and Braham, who indicate that downdrafts are less intense and lower than updrafts. In Figure 2, the region between the updraft and downdraft cores is one of very strong horizontal shear (i.e., turbulence). Although constrained by the TSTORM parameterization of $W = 0$ at top and bottom, careful inspection of Figure 2 reveals that the updraft tends to "shoot" toward the middle top of the storm, while the downdraft core descends conspicuously toward the surface. At low levels (near surface to 2 km) below the updraft, the isotach $W = 0$, which represents the forward outflow boundary of the downdraft, is observed to have a pronounced negative vertical tilt. Finally, at values of absolute x near one, vertical velocities depicted in Figure 2 are quite small; such benign values represent pre- and post-storm conditions or, vertical motion sufficiently removed from the storm's periphery.

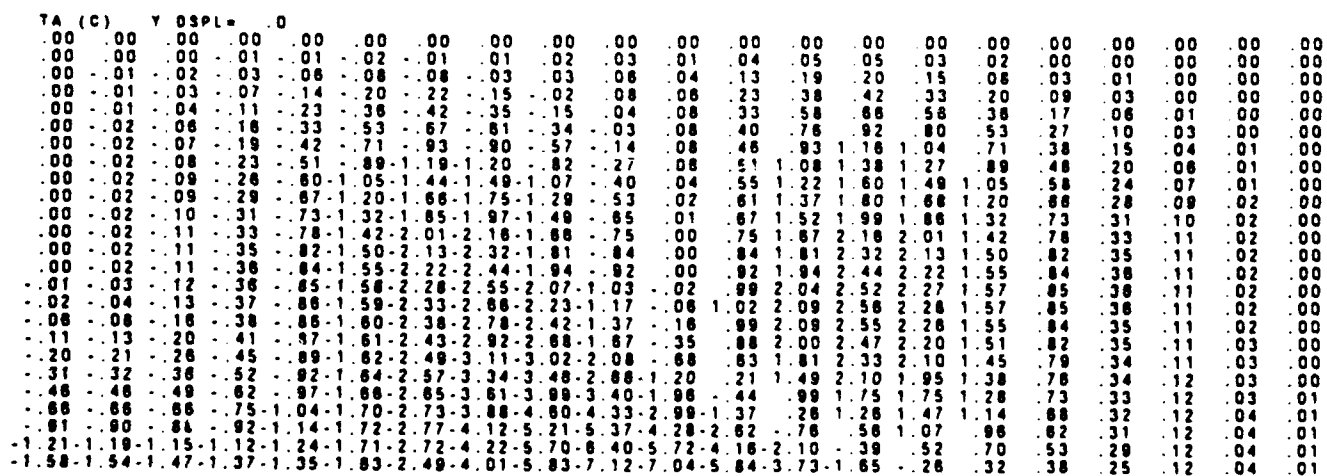


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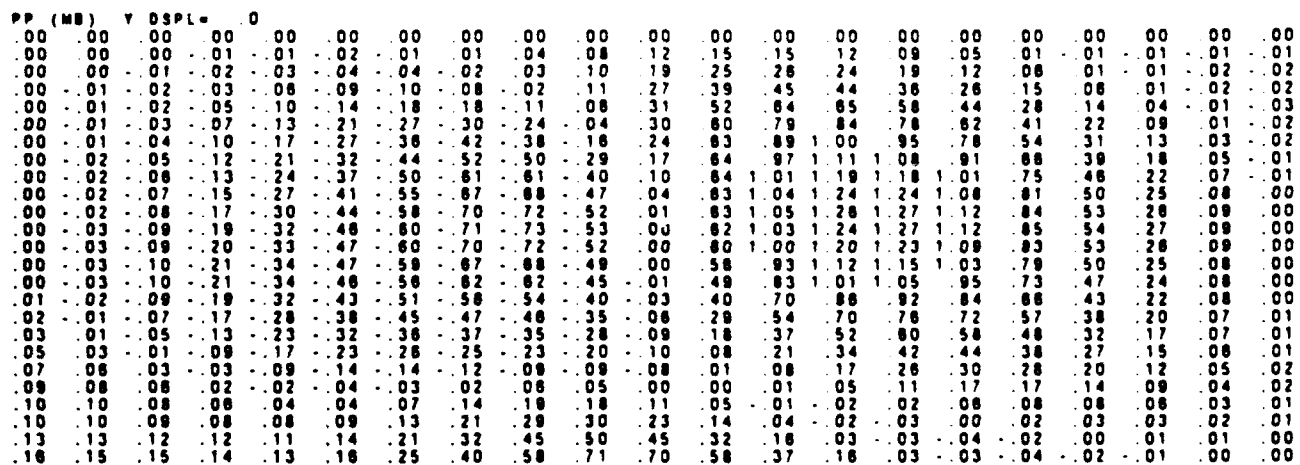
The temperature anomaly vertical cross section (Figure 3) is dominated by two opposing cores. Within the storm's forward sector, a positive anomaly core of about 2.5 C is located a few kilometers below the updraft maximum. Related to the storm's downdraft, cold temperature anomalies of magnitude 1 to 2 C are found at mid-levels, increasing appreciably toward the surface, with a maximum negative anomaly in excess of 7 C at the surface below the downdraft. The 0 C isotherm which underlies the updraft in a wedge-like fashion corresponds to the leading edge of the cold air outflow beneath the storm. Note that the temperature anomaly gradient at the surface is very strong from the time of the arrival of the outflow ($x = 0.4$) to the time of the storm's apex ($x = 0$). Once beyond the storm's center, the surface temperature anomaly rises steadily before leveling off at about -1.5 C for $x \leq -0.5$. These negative surface temperature anomalies at large negative x simulate the cool air left in the storm's wake. On the forward perimeter of the storm, at the pre-storm stage (i.e., near $x = 1$), TSTORM produces little if any anomaly from the outside environment at any level.

The vertical cross section of the pressure perturbation (Figure 4) shows two opposing anomaly cores at mid-level; a weaker negative P_p core of about -0.7 mb within the downdraft and a stronger positive P_p core exceeding 1.2 mb within the updraft. At the surface and lower levels, the TSTORM test case exhibits a very slight pressure reduction below the updraft and a prominent pressure dome of about +0.7 mb below the downdraft at the center of the storm. Inspection of tabular results of Figure 4 reveals that the surface pressure dome anomaly initially decreases after the storm's apex, then levels off to about +0.15 mb at large negative x (i.e., at $x \leq -0.5$).

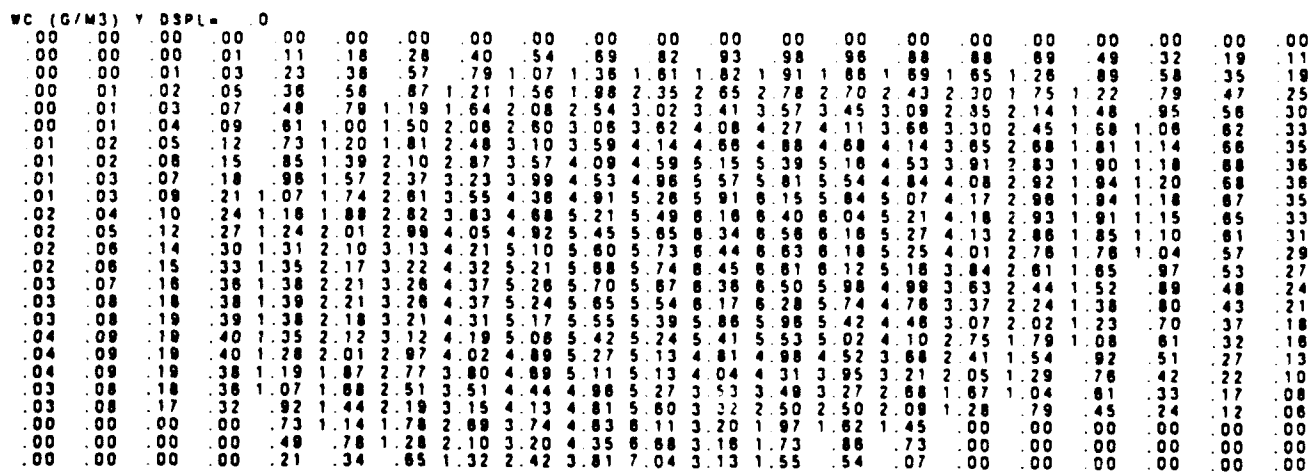
As given by the vertical cross section of total water content (Figure 5), the shape of the test simulation thunderstorm cell is basically cylindrical. However, on close inspection, one can discern a skewness in total water content at middle to upper levels in the direction of storm



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motion (i.e., in the +x direction), with significantly higher values of WC ahead of the storm ($x > 0.8$) than in the rear ($x < -0.8$). Within the thunderstorm cell, a large concentration of water content ($> 5.5 \text{ g m}^{-3}$) is found at middle levels, covering the inner storm region between the updraft and downdraft cores. Below 3 km, the storm's highest total water content becomes concentrated within a narrow band, forming a rain shaft which drops to the surface at the storm's center ($x = 0$). Based on Blanchard's empirical relation, the maximum value $\text{WC} = 7 \text{ gm}^{-3}$ at the storm's apex corresponds to a (3 minute average) rainfall rate of 140 mm/hr.¹ This simulated thunderstorm would produce a total of about 21 mm (0.83 in) of rain in about half an hour (i.e., during the time $-0.6 \leq x \leq 0.4$) at a site directly in the storm's path.

In the test simulation, the vertical wind structures during pre- and post-storm conditions are nearly identical. At these times, horizontal winds are observed to veer steadily with height (from surface easterly to upper level westerlies), with speed increasing gradually from the surface to mid-levels, then more rapidly to the storm's top (Figures 6 and 7). Within the thunderstorm cell close to its vertical axis (i.e., near $x = 0$), the wind structure is much more varied. At the top, westerly winds of 15 m/s decrease rapidly toward a mid-level core of very light winds, with an absolute minimum of 0 m/s at $(x,z) = (0,6)$. Below this inner storm minimum, winds first increase slowly toward the surface, then very rapidly once inside the surface cold air downdraft. Within the confines of the cold air outflow, wind directions are divergent from the storm's center. The arrival of the surface "gust front" is marked by a sudden shift in wind direction (from 90 deg at $x = 0.6$ to 270 deg at $x = 0.5$) and a rapid increase in wind speed from 3 to 10 m/s in about 10 minutes. Once the apex of the storm passes, surface horizontal wind speeds decrease rapidly, falling below 3 m/s at $x = -0.4$.

¹For this and any simulation, the storm maximum rainfall rate can be found by multiplying the storm depth H (km) by $11.7 \text{ mm hr}^{-1} \text{ km}^{-1}$.

[illegible]

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3.2 Horizontal Cross Sections

For the test case simulation, plots of horizontal (x,y) cross sections were made for all computed meteorological fields for both the surface (except $z = 0.5$ km for W) and the mid-storm level ($z = 6$ km). In order to easily interpret horizontal dimensions of thunderstorm features, the length of the TSTORM grid y-axis is assumed equal to that of the x-axis, that is, 20 km.

Given the bottom boundary condition $W = 0$, values of the vertical velocity just above the surface (at $z = 0.5$ km) are predictably small (Figure 8a); nonetheless, the thunderstorm cell's almost circular downdraft is clearly evident near the center of the TSTORM grid. At mid-level (Figure 8b), a two-lobed, updraft-downdraft pattern is well defined. Here, both the updraft and downdraft exhibit elliptical structure, with the outer contours of each appreciably elongated in the y-direction.

The horizontal cross sections of temperature anomaly at the surface and $z = 6$ km are quite distinct (Figure 9). At mid-level, two opposing cores of T_a of similar magnitude (about 2 C) are evident; much like the vertical velocity, the shape of the positive and negative T_a patterns are elliptical, being elongated in the y-direction. The (x,y) cross section plot at the surface is dominated by the very prominent temperature deficit associated with the cold air outflow beneath the downdraft. Contours of this feature are observed to be slightly elliptical within 0.4 units of the center. The open contours at $x < -0.6$ represent cooler surface conditions in the wake of the storm, that is, post-storm locations where the temperature has not recovered to pre-storm levels.

In general, the horizontal cross sections of the pressure perturbation appear quite similar to those of the vertical velocity. At the surface (Figure 10a), the closed contours near the grid center describe the spatial structure of the storm's pressure dome beneath the downdraft. At mid-level (Figure 10b), a two-lobed, elliptical contour structure is evident, with the positive P_p core (related to the updraft) about double the magnitude of the weaker negative P_p core.

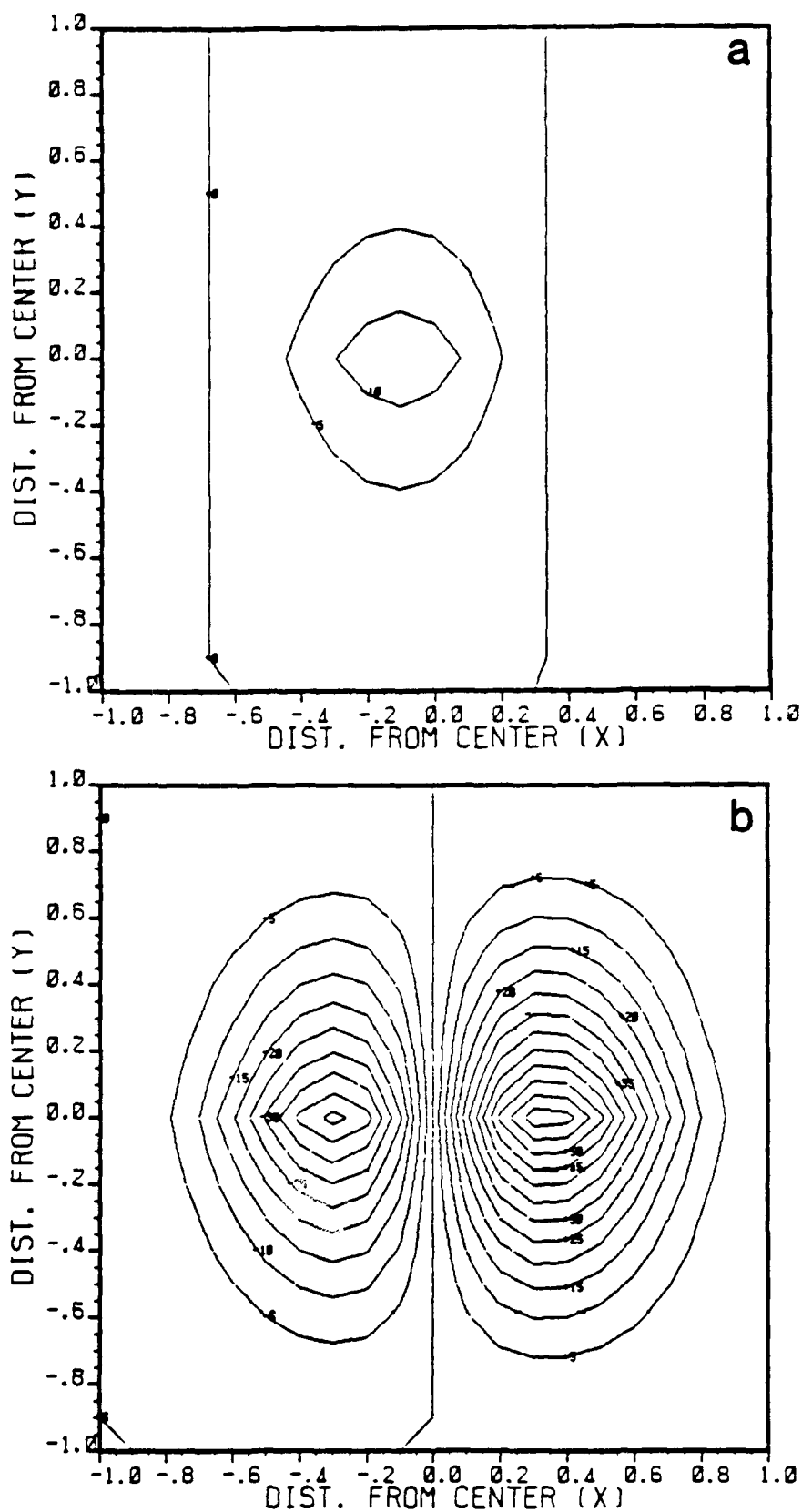


Figure 8. Test case horizontal cross sections of vertical velocity W . a) at $z = 0.5$ km, b) at $z = 6$ km. Plot contours range from -1.0 to 0.0 m/s in a) and from -4.5 to 6.0 m/s in b), both in intervals of 0.5 m/s.

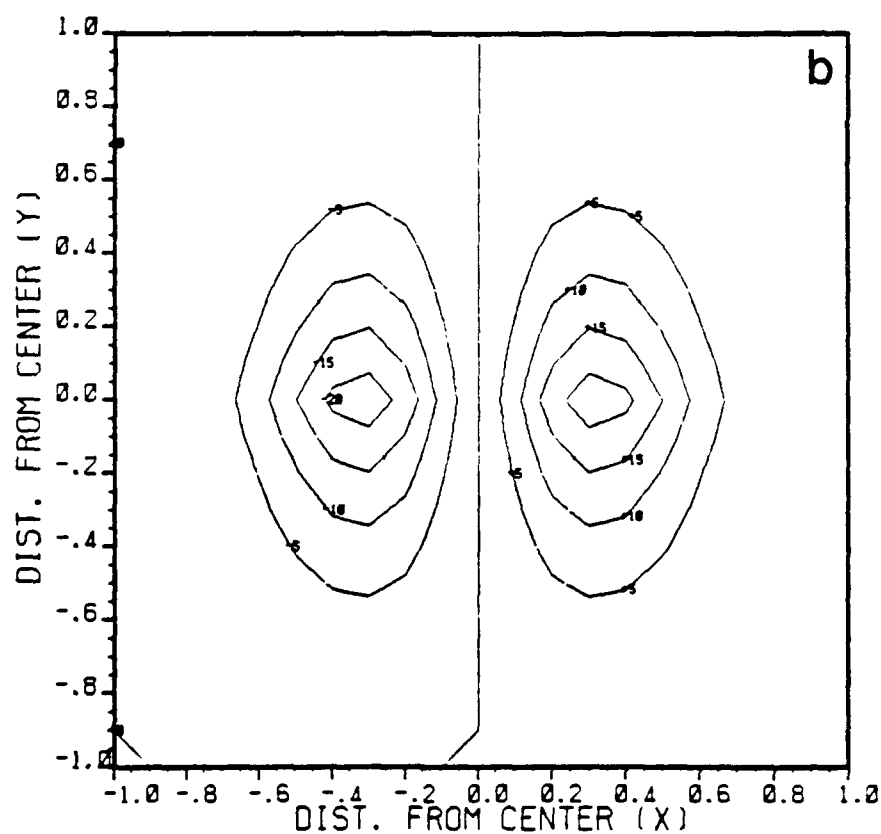
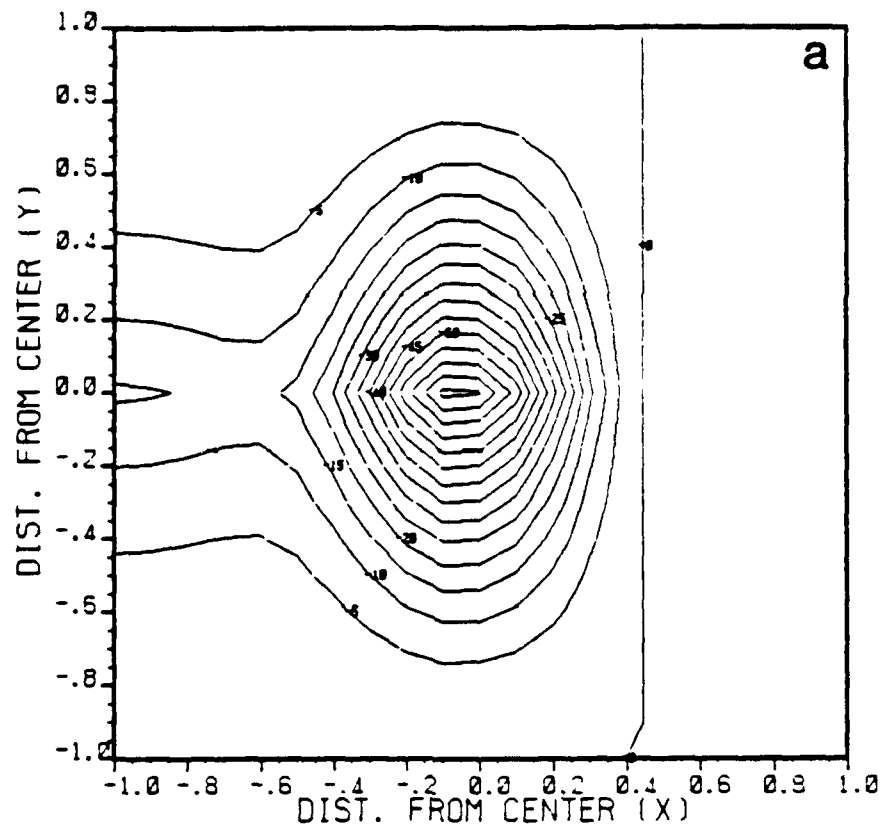


Figure 9. Test case horizontal cross sections of temperature anomaly T_a . a) at $z = 0$ km, b) at $z = 6$ km. Plot contours range from -7.0 to 0.0 C in a) and from -2.0 to 2.0 C in b), both in intervals of 0.5 C.

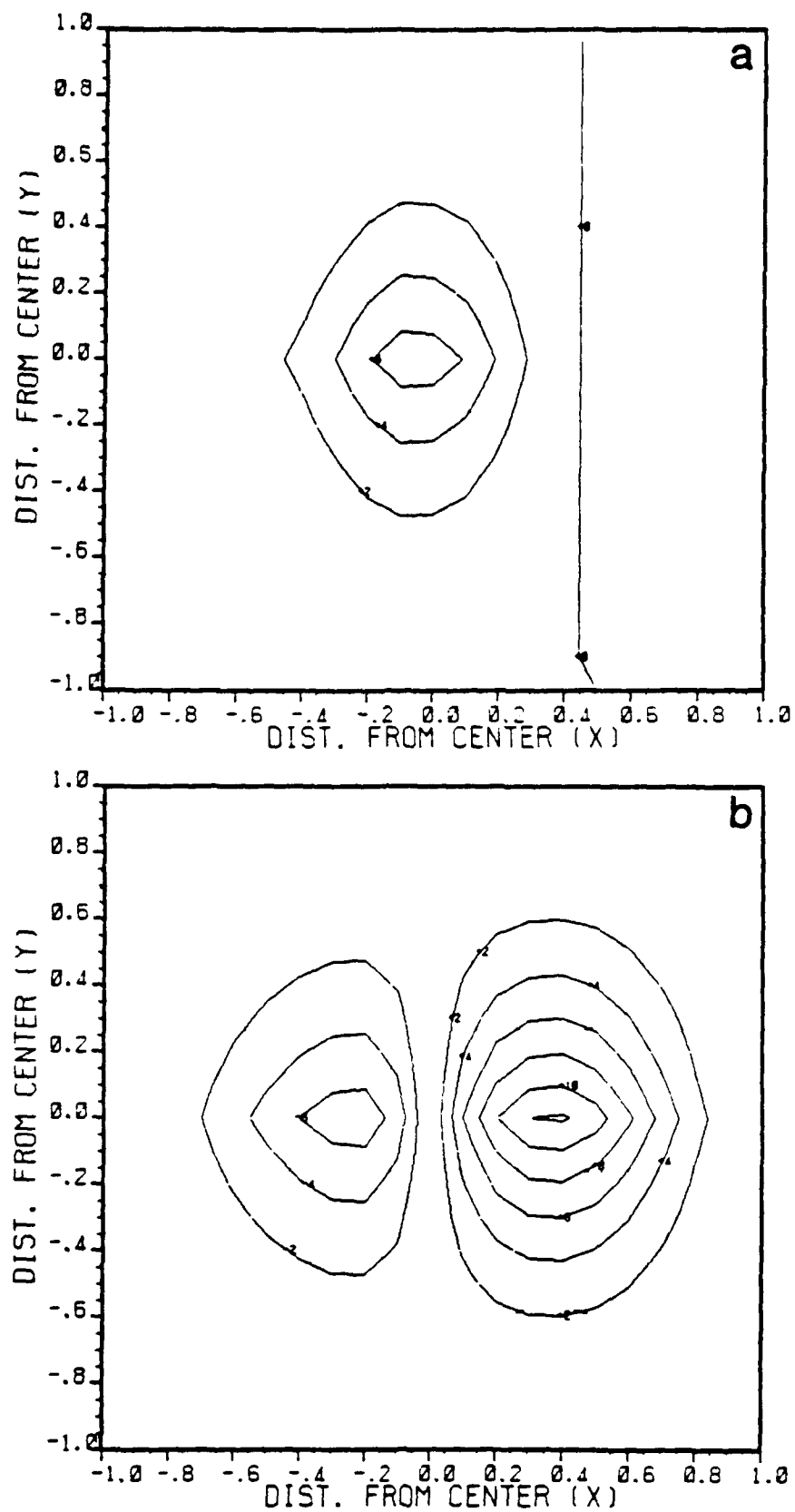


Figure 10. Test case horizontal cross sections of pressure perturbation P_p . a) at $z = 0$ km, b) at $z = 6$ km. Plot contours range from 0.0 to 0.6 mb in a) and from -0.6 to 1.2 mb in b), both in intervals of 0.2 mb.

The surface horizontal cross section of the total water content (Figure 11a) delineates the spatial structure of the precipitation field. Here, the smallest contour (0.5 g m^{-3}) corresponds to a moderate rainfall rate of 10 mm/hr; the area within this contour is quite small, being about 40 km^2 . As to be expected, the very intense rainfall rate ($\text{RR} > 100 \text{ mm/hr}$) of the simulated thunderstorm is concentrated over a very small area (several km^2) at the storm's center.

The horizontal structure of the thunderstorm cloud at mid-level is given in Figure 11b. Here, the shape of the WC contours are elliptical, with the x-axis being the major axis. The inner contours of high total water content are markedly flattened; note the lateral extension in the negative x-direction from the core maximum at $x = 0.2$ units. At this level ($z = 6 \text{ km}$), the contours of WC are noticeably skewed toward the right (i.e., in the $+x$ direction). Given the assumed (x,y) spatial dimensions, the thunderstorm cloud at this level extends over a horizontal area of a few hundred square kilometers.

As formulated in TSTORM, contours of horizontal wind speed are essentially circular. In Figure 12a, the outer contour ($\text{WS} = 3 \text{ m/s}$) represents the outward extent of winds (i.e., the gust front) beneath the storm; in terms of assumed horizontal dimensions for this simulation, this boundary occurs at about 4 km from the storm's center. At mid-level (Figure 12b), horizontal winds on the storm's perimeter (in this simulation, of speed 6.5 m/s) decrease steadily toward the center core of the storm.

The surface wind vectors of Figure 13a indicate that within the confines of the gust front, winds blow radially outward from the storm center, with increasing speed toward the center; outside of the gust front, winds are uniform (viz., easterly at 2.8 m/s). At mid-storm level (Figure 13b), horizontal winds are deflected and slow down as they approach the storm center; once past the inner core, winds converge and speed up, eventually exiting the storm environment with a wind speed and direction equal to that of the environmental wind (viz., 217 deg and 6.5 m/s).

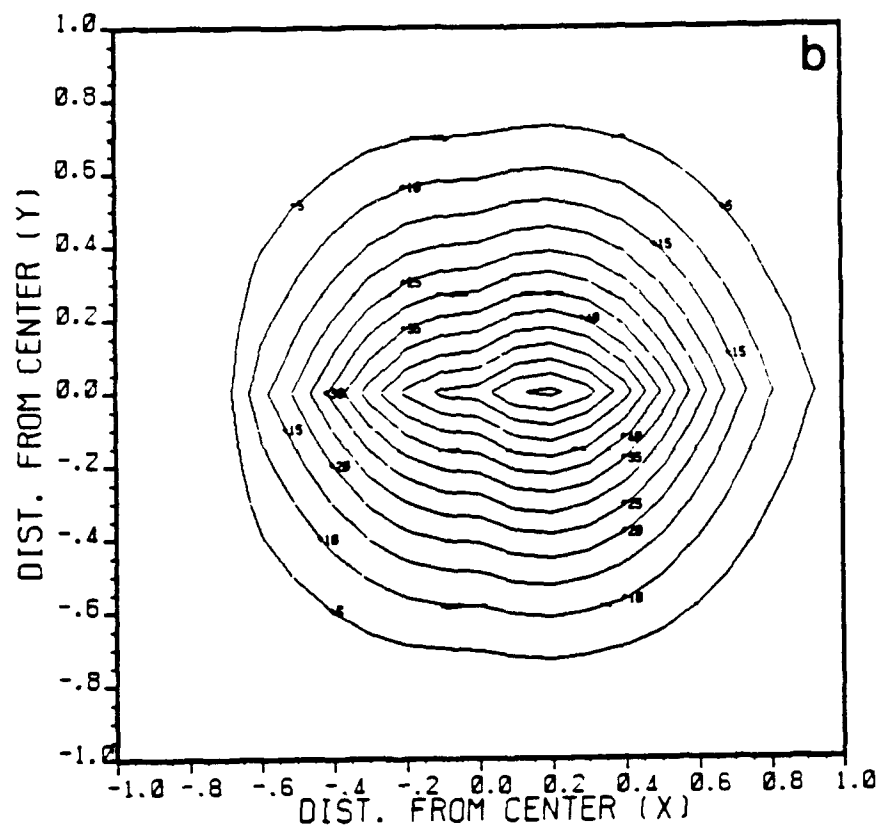
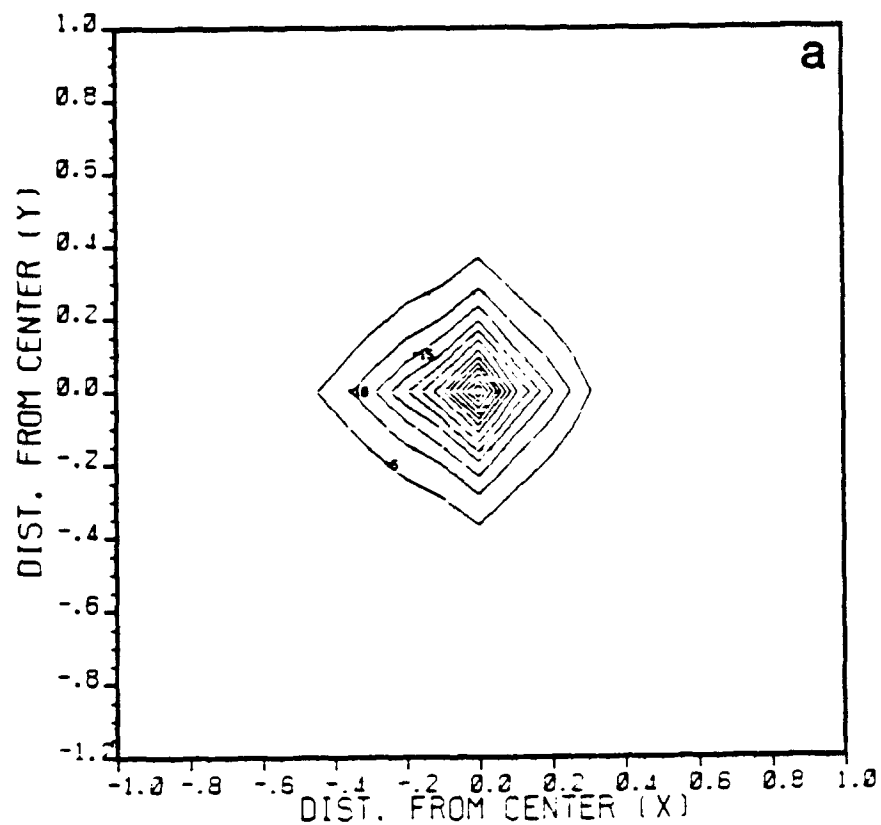


Figure 11. Test case horizontal cross sections of total water content WC. a) at $z = 0$ km, b) at $z = 6$ km. Plot contours range from 0.5 to 6.5 g m^{-3} in both a) and b), at intervals of 0.5 g m^{-3} .

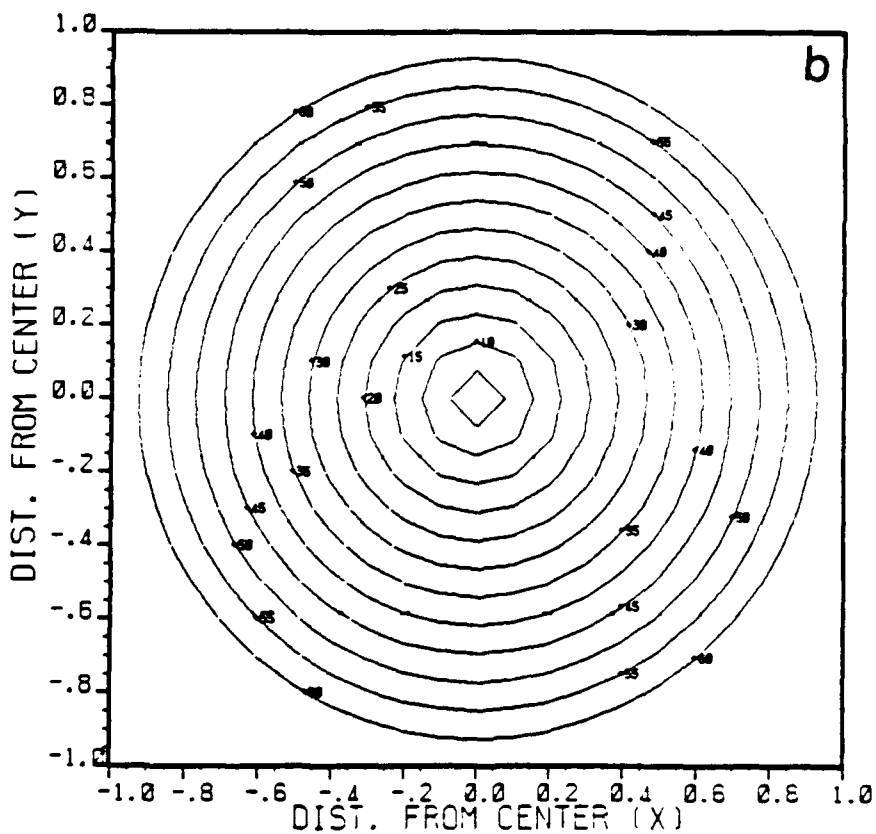
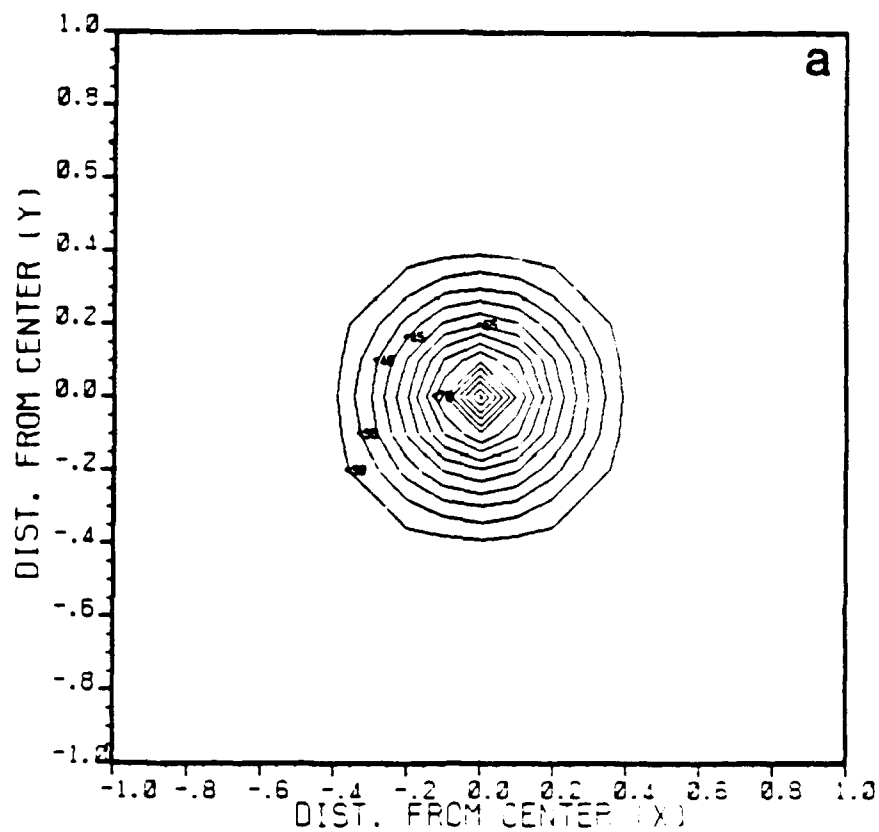


Figure 12. Test case horizontal cross sections of wind speed WS. a) at $z = 0$ km, b) at $z = 6$ km. Plot contours range from 3.0 to 10.0 m/s in a) and from 0.5 to 6.0 m/s in b), both in intervals of 0.5 m/s.

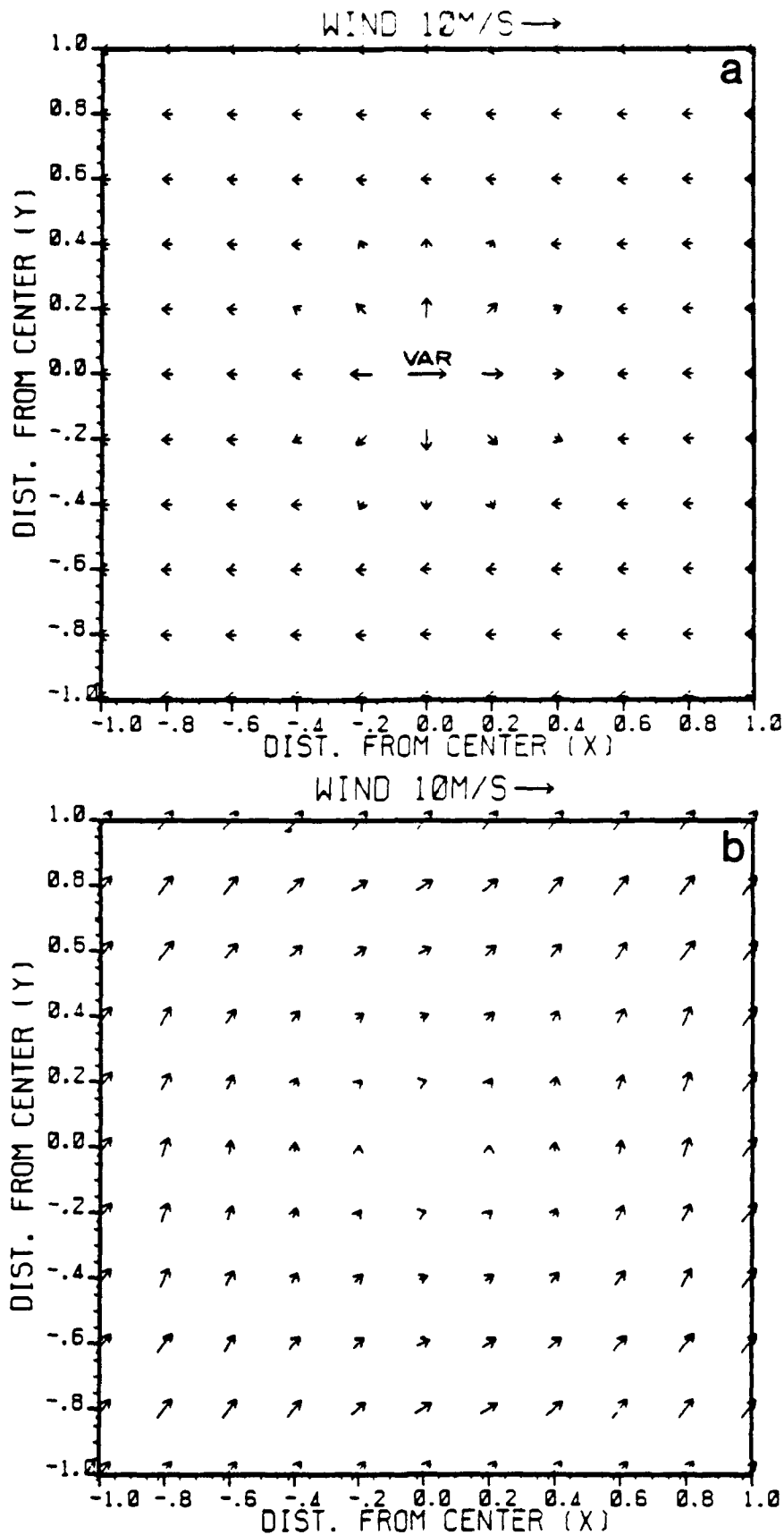
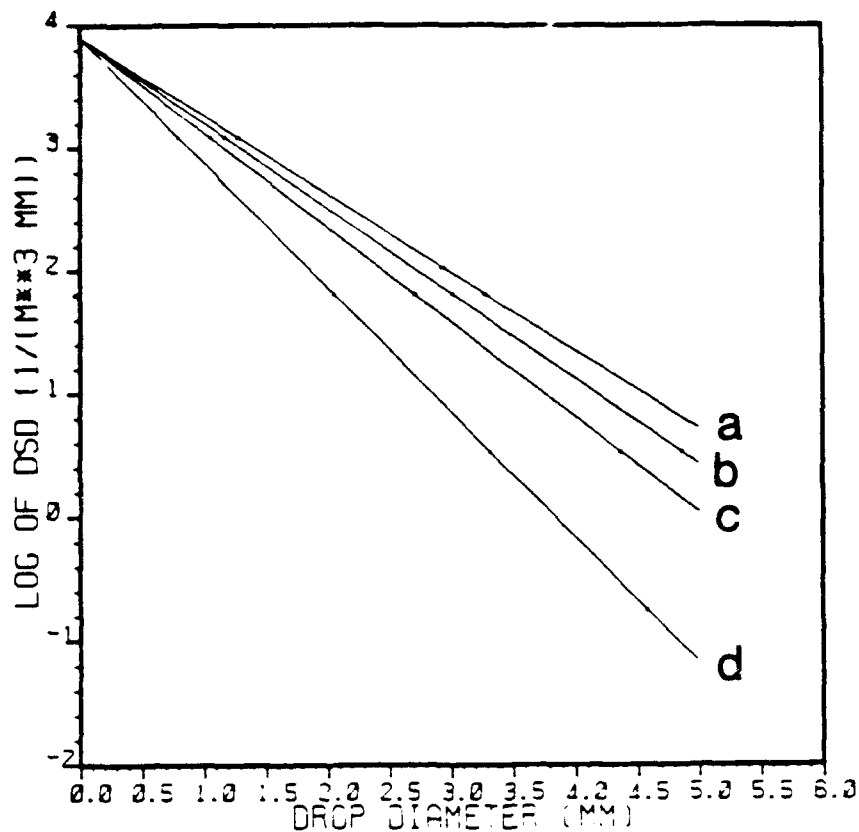


Figure 13. Test case horizontal cross sections of wind vectors. a) at $z = 0$ km, b) at $z = 6$ km. Plot scale represents a westerly wind of 10 m/s. Note: at coordinates (0,0,0), the wind direction is variable; at (0,0,6), the horizontal wind is zero.

3.3 Dropsize Distribution

In the test simulation, Marshall- Palmer dropsize distributions were computed at four sites within the lower thunderstorm cloud structure. Figure 14 presents these dropsize distribution results in both graphical and tabular form. For interpretation of results, the actual number of drops per cubic meter, of diameter between D and $D + \delta D$ (where δD is preset to 0.25 mm), is obtained as the product of the distribution function DSD and δD ; for example, at site a), the number of drops of diameter 3.25 to 3.5 mm in a cubic meter of air would be $68 * 0.25$, or 17 drops.

At any particular site, and for a specified drop diameter, the actual dropsize distribution is determined by the rainfall rate RR which, in turn, is a direct function of the total water content. Generally, for a fixed drop diameter, the number of drops per cubic meter of air is in direct proportion to the rainfall rate - the higher the rate, the more drops. Of the sites chosen for this simulation, the dropsize distribution is largest at site a), which is located just above the surface in the rain shaft, and least at site d), located slightly above the ground in lightly descending air at $x = -0.6$ units. Careful inspection of Figure 14 indicates that, while the actual difference in the number of drops between these two sites is largest at small diameters (excepting $D = 0$), the percent difference is largest at large diameters, where there are far fewer drops per cubic meter. For all sites a) through d), the distribution function DSD (in $\text{mm}^{-1} \text{m}^{-3}$) decreases exponentially with drop diameter, from several thousand at small drop diameters to about 10 or less at diameters near 5 mm.



X= .0 Y= .0 Z= .5KM RR= 133.6MM/HR

D(MM)	DSD (1/(MM ³ MM))
.00	8000.0
.25	5544.1
.50	3842.1
.75	2662.6
1.00	1845.2
1.25	1278.8
1.50	886.2
1.75	614.1
2.00	425.8
2.25	294.9
2.50	204.4
2.75	141.7
3.00	98.2
3.25	68.0
3.50	47.1
3.75	32.7
4.00	22.6
4.25	15.7
4.50	10.9
4.75	7.5
5.00	5.2

a

X= -.2 Y= .0 Z= 2.0KM RR= 88.7MM/HR

D(MM)	DSD (1/(MM ³ MM))
.00	8000.0
.25	5364.7
.50	3597.5
.75	2412.4
1.00	1617.7
1.25	1084.8
1.50	727.5
1.75	487.8
2.00	327.1
2.25	219.4
2.50	147.1
2.75	98.6
3.00	66.2
3.25	44.4
3.50	29.7
3.75	19.9
4.00	13.4
4.25	9.0
4.50	6.0
4.75	4.0
5.00	2.7

b

X= .4 Y= .0 Z= 2.0KM RR= 53.6MM/HR

D(MM)	DSD (1/(MM ³ MM))
.00	8000.0
.25	5130.3
.50	3289.9
.75	2109.8
1.00	1353.0
1.25	867.6
1.50	556.4
1.75	356.8
2.00	228.8
2.25	148.7
2.50	94.1
2.75	60.3
3.00	38.7
3.25	24.8
3.50	15.9
3.75	10.2
4.00	6.5
4.25	4.2
4.50	2.7
4.75	1.7
5.00	1.1

c

X= -.6 Y= .0 Z= 1.0KM RR= 14.5MM/HR

D(MM)	DSD (1/(MM ³ MM))
.00	8000.0
.25	4459.5
.50	2485.9
.75	1385.7
1.00	772.5
1.25	430.6
1.50	240.0
1.75	133.8
2.00	74.6
2.25	41.6
2.50	23.2
2.75	12.9
3.00	7.2
3.25	4.0
3.50	2.2
3.75	1.2
4.00	.7
4.25	.4
4.50	.2
4.75	.1
5.00	.1

d

Figure 14. Test case drops size distributions at selected cloud locations. a) at (0,0,0.5), b) at (-0.2,0,2.0), c) at (0.4,0,2.0) and d) at (-0.6,0,1.0). The rainfall rate RR (mm/hr) is also given for each location.

REFERENCES

- Blanchard, D.C., 1953: Raindrop Size-Distribution in Hawaiian Rains. Journal of Meteorology, Vol. 10, No. 6, pp 457-473.
- Byers, H.R. and R.R. Braham, Jr., 1949: The Thunderstorm; Report of the Thunderstorm Project. U.S. Government Printing Office, Washington, D.C., 297 pp.
- Kessler, Edwin, 1969: On the Distribution and Continuity of Water Substance in Atmospheric Circulation. Meteorological Monographs, Vol. 10, No. 32, American Meteorological Society, Boston, MA, 84 pp.
- Marshall, J.S. and W. McK. Paimer, 1948: The Distribution of Raindrops with Size. Journal of Meteorology, Vol. 5, No. 4, pp 165-166.

APPENDIX - TSTORM COMPUTER LISTING

[illegible]

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C
C               TSTORM
C      A FEATURE MODEL OF A THUNDERSTORM CELL
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CCCCCCCCCCCCCCCCCCCCC  MAIN PROGRAM  CCCCCCCCCCCCCCCCCCCCCC

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C	INPUTS	VARIABLE	DESCRIPTION	(VALID RANGE, UNITS)
C		NLVL	NUMBER OF LEVELS	13-31
C		H	THUNDERSTORM HEIGHT	[6., 6.5...14.5, 15.] KM
C		WMAX	MAX. VERT. VELOCITY	6.- 15. M/S
C		VMAX	WIND SPEED AT LEVEL H	10.- 30. M/S
C		WDSFC	SFC. WIND DIRECTION	0.- 360. DEG
C		VEER	WIND VEER, SFC. TO H	+ - 360. DEG
C		NLOC	NO. OF SITES FOR DROPSIZE DSTR.	>= 1
C		XDSD(NLOC)	X-COORDINATE FOR NLOC SITE	[-1.-, -0.9...0.9, 1.]
C		YDSD(NLOC)	Y-COORDINATE FOR NLOC SITE	[-1.-, -0.9...0.9, 1.]
C		ZDSD(NLOC)	Z-COORDINATE FOR NLOC SITE	[0., 0.5...4.5, 5.] KM

C	OUTPUTS	VARIABLE	DESCRIPTION	(VALID RANGE,UNITS)
C		W(21,21,NLVL)	VERTICAL VELOCITY ARRAY	M/S
C		TA(21,21,NLVL)	TEMPERATURE ANOMALY ARRAY	C
C		PP(21,21,NLVL)	PRESSURE PERTURBATION ARRAY	MB
C		WC(21,21,NLVL)	TOTAL WATER CONTENT ARRAY	G/M3
C		WS(21,21,NLVL)	WIND SPEED ARRAY	M/S
C		WD(21,21,NLVL)	WIND DIRECTION ARRAY	DEG
C		DD(21)	DROP DIAMETER ARRAY [0..0.25...4.75,5.]	MM
C		DSD(NLOC,21)	DROPSIZE DISTRIBUTION ARRAY	
C		RR(NLOC)	RAINFALL RATE AT NLOC SITE	MM/HR

C THE TSTORM ALGORITHM IS A FEATURE MODEL WHICH PROVIDES A SIMPLE
C PARAMETRIC REPRESENTATION OF A THUNDERSTORM CELL. IT IS DESIGNED
C FOR USE IN SIMULATIONS REQUIRING AN IDEALIZED MAGNITUDE AND SPATIAL
C DISTRIBUTION OF METEOROLOGICAL PARAMETERS WITHIN A THUNDERSTORM.
C TSTORM OUTPUT MAY BE SUPERIMPOSED ON AN INITIAL DATA FIELD TO
C PROVIDE ADDED SUBGRID INFORMATION OR TIME VARIABILITY, OR MAY BE
C USED AS A UNIQUE ENVIRONMENTAL SOURCE FOR THE HOST SIMULATION.

C THE FOLLOWING PROGRAM, WRITTEN IN ANSI FORTRAN 77, IS A DEMONSTRATION DRIVER FOR THE TSTORM SUBROUTINE. BASED ON THE PHYSICAL INPUT PARAMETERS, THIS SIMULATION CORRESPONDS TO A THUNDERSTORM OF A HEAVY INTENSITY. AFTER RETURN FROM THE TSTORM SUBROUTINE, THE DRIVER PROGRAM OUTPUTS (IN TABULAR FORM) SEVERAL VERTICAL CROSS SECTIONS AND DROPSIZE DISTRIBUTIONS FOR THE SIMULATED THUNDERSTORM.

C START DEMO PROGRAM

PROGRAM TSMODL

C ENTER ARRAY PARAMETERS

```
PARAMETER(NLVL=25)
PARAMETER(NLOC=4)
```

CHARACTER=10 TITLE1(6)
CHARACTER=8 TITLE2(1)

```

DIMENSION W(21,21,NLVL),TA(21,21,NLVL),PP(21,21,NLVL)
DIMENSION WC(21,21,NLVL),WS(21,21,NLVL),WC(21,21,NLVL)
DIMENSION DD(21),DSD(NLOC,21),RR(NLOC)
DIMENSION XDSD(NLOC),YDSD(NLOC),ZDSD(NLOC)

```

```
DATA TITLE1(1)/' W (M/S) '/
DATA TITLE1(2)/' TA (C)  '/
```

```

DATA TITLE1(3)/' PP (MB) '/
DATA TITLE1(4)/' WC (G/M3) '/
DATA TITLE1(5)/' WS (M/S) '/
DATA TITLE1(6)/' WD (DEG) '/
C
DATA TITLE2(1)/' Y DSPL=' /
C
C
C
ENTER DSD LOCATIONS
DATA XDSD/0.0,0.4,-0.2,-0.6/
DATA YDSD/0.0,0.0,0.0,0.0/
DATA ZDSD/0.5,2.0,2.0,1.0/
C
YPLT = 0.0
C
C
C
ENTER PHYSICAL PARAMETERS
H = 12.
WMAX = 9.
VMAX = 15.
WDSFC = 90.
VEER = 180.
C
OPEN(7,FILE='OUTFIL',STATUS='NEW')
C
C
C
CALL TSTORM SUBROUTINE.
C
CALL TSTORM(NLVL,H,WMAX,VMAX,WDSFC,VEER,NLOC,XDSD,YDSD,ZDSD,
=W,TA,PP,WC,WS,WD,DD,DSD,RR)
C
C
C
WRITE OUTPUT FILES.
C
YR = (YPLT + 1.1) * 10.
J = INT(YR)
C
DO 100 NP = 1,6
C
WRITE(7,200) TITLE1(NP),TITLE2(1),YPLT
200 FORMAT(A10,A8,F4.1)
C
DO 300 K = 1,NLVL
C
KL = 1 + (NLVL-K)
C
IF(NP.EQ.1) WRITE(7,400) (W(I,J,KL),I=1,21)
IF(NP.EQ.2) WRITE(7,400) (TA(I,J,KL),I=1,21)
IF(NP.EQ.3) WRITE(7,400) (PP(I,J,KL),I=1,21)
IF(NP.EQ.4) WRITE(7,400) (WC(I,J,KL),I=1,21)
IF(NP.EQ.5) WRITE(7,400) (WS(I,J,KL),I=1,21)
IF(NP.EQ.6) WRITE(7,500) (WD(I,J,KL),I=1,21)
400 FORMAT(21F5.2)
500 FORMAT(21F5.1)
C
300 CONTINUE
C
100 CONTINUE
C
DO 600 NL = 1,NLOC
C
WRITE(7,700) XDSD(NL),YDSD(NL),ZDSD(NL),RR(NL)
700 FORMAT(' X=',F5.1,' Y=',F5.1,' Z=',F5.1,' KM RR=',
F6.1,' MM/HR')
WRITE(7,800)
800 FORMAT(' D(MM) DSD (1/(M**3 MM))')
C
DO 900 ND = 1,21
C

```

```

1000      WRITE(7,1000) DD(ND),DSD(NL,ND)
          FORMAT(F5.2,9X,F7.1)
C
C 900      CONTINUE
C
C 600 CONTINUE
C
C      STOP
C
C
C      END DEMO PROGRAM
C
C      END
C
CCCCCCCCCCCCCCCC START SUBROUTINE TSTORM CCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
SUBROUTINE TSTORM(NLVL,H,WMAX,VMAX,WDSFC,VEER,NLOC,XDSD,YDSD,ZDSD,
  *W,TA,PP,WC,WS,WD,DD,DSD,RR)
C
C INPUTS VARIABLE      DESCRIPTION      (VALID RANGE,UNITS)
C      NLVL            NUMBER OF LEVELS      13-31
C      H              THUNDERSTORM HEIGHT    [6.,6.5...14.5,15.] KM
C      WMAX           MAX. VERT. VELOCITY    6.- 15. M/S
C      VMAX           WIND SPEED AT LEVEL H   10.- 30. M/S
C      WDSFC          SFC. WIND DIRECTION     0.- 360. DEG
C      VEER           WIND VEER, SFC. TO H    +- 360. DEG
C      NLOC           NO. OF SITES FOR DROPSIZE DSTR. >= 1
C      XDSD(NLOC)     X-COORDINATE FOR NLOC SITE [-1.,-0.9...0.9,1.]
C      YDSD(NLOC)     Y-COORDINATE FOR NLOC SITE [-1.,-0.9...0.9,1.]
C      ZDSD(NLOC)     Z-COORDINATE FOR NLOC SITE [0.,0.5...4.5,5.] KM
C
C OUTPUTS VARIABLE      DESCRIPTION      (VALID RANGE,UNITS)
C      W(21,21,NLVL)   VERTICAL VELOCITY ARRAY      M/S
C      TA(21,21,NLVL)   TEMPERATURE ANOMALY ARRAY    C
C      PP(21,21,NLVL)   PRESSURE PERTURBATION ARRAY   MB
C      WC(21,21,NLVL)   TOTAL WATER CONTENT ARRAY     G/M3
C      WS(21,21,NLVL)   WIND SPEED ARRAY              M/S
C      WD(21,21,NLVL)   WIND DIRECTION ARRAY          DEG
C      DD(21)           DROP DIAMETER ARRAY           [0.,0.25...4.75,5.] MM
C      DSD(NLOC,21)     DROPSIZE DISTRIBUTION ARRAY
C      RR(NLOC)         RAINFALL RATE AT NLOC SITE     MM/HR
C
C      DIMENSION W(21,21,NLVL),TA(21,21,NLVL),PP(21,21,NLVL)
C      DIMENSION WC(21,21,NLVL),WS(21,21,NLVL),WD(21,21,NLVL)
C      DIMENSION DD(21),DSD(NLOC,21),RR(NLOC)
C      DIMENSION XDSD(NLOC),YDSD(NLOC),ZDSD(NLOC)
C
C      PI = 4.*ATAN(1.)
C      DEGRAD = 180./PI
C
C      HB = H/12.
C      H6 = H/6.
C      H3 = H/3.
C      H2 = H/2.
C      HT = H - H/12.
C
C      DO 100 K = 1,NLVL
C
C          Z = -0.5 + 0.5*K
C
C          DO 200 I = 1,21
C
C              RX = -1.1 + 0.1*I
C
C          CALCULATE THE VERTICAL VELOCITY.
C
C              RXDPL = RX - ( 0.432 * ((H2-Z)/H2)**3 )
C              W1 = EXP(-PI*RX*RX)

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      W2 = SIN(PI*RXDPL)
      W3 = W1*W2
C
      W4 = (4*WMAX/H)*(Z - Z*Z/H)
      W5 = (1 + Z*RX/H)
C
      WCAL = W3*W4*W5
C
      CALCULATE THE TEMPERATURE ANOMALY.
C
      T1 = EXP(-PI*RX*RX) * (0.3/H2) * (H-Z)**2
      T2 = 1 + ((Z*Z*ABS(RX))/(H*H/24.))
      T3 = EXP(RX) * RX * ( 4.32 * ((H2-Z)/H2)**3 )
C
      TACAL = W3*T1*T2
      IF(RX.LE.0. .AND. Z.LE.H2) TACAL = TACAL + T3
C
      CALCULATE THE PRESSURE PERTURBATION.
C
      IF(Z.LE.HB .OR. Z.GE.HT) PPCAL = 0.1* (WCAL-TACAL)
      IF(Z.GT.HB .AND. Z.LT.HT)
      *   PPCAL = 0.1* (WCAL-TACAL) * (Z - Z*Z/H)
C
      CALCULATE THE TOTAL WATER CONTENT (LIQUID + SOLID)
C
      WC1 = ABS(TACAL) * ( 1 - (ABS(RX)**0.333))
      WC2 = 2 * (Z - Z*Z/H) * EXP ( -PI * ((RX- 0.12*Z/H2)**2))
      WCCAL = WC1 + WC2
      IF((RX.GE.0.4 .OR. RX.LT.-0.6).AND. Z.LE.HB) WCCAL = 0.0
      IF((RX.GE.0.4 .OR. RX.LT.-0.6).AND. Z.GT.HB)
      *   WCCAL = WCCAL * EXP(-RX*RX) * (1 + Z*RX/H)
C
      DO 300 J = 1,21
C
      RY = -1.1 + 0.1*J
      RYFAC = (1.0 - ABS(RY))**2
C
      SPECIFY WCAL,TACAL,PPCAL AND WCCAL AT (I,J,K) COORDINATES.
C
      W(I,J,K) = WCAL * RYFAC
      TA(I,J,K) = TACAL * RYFAC
      PP(I,J,K) = PPCAL * RYFAC
      WC(I,J,K) = WCCAL * RYFAC
      IF(Z.LT.H6) WC(I,J,K) = WC(I,J,K) * (RYFAC**(H6-Z))
C
      CALCULATE THE HORIZONTAL WIND SPEED AND DIRECTION.
C
      VE = VMAX * EXP(-1.68 * (H-Z)/H )
C
      WDE = WDSFC + (VEER * SIN((PI*Z)/(2*H)) )
      IF(WDE.GT.360.) WDE = WDE - 360.
      IF(WDE.LE.0.) WDE = WDE + 360.
C
      IF(Z.LE.H6) RXH = RX + ( (0.16/H6) * Z )
      IF(Z.GT.H6 .AND. Z.LT.(H-H6))
      *   RXH = RX + ( (0.16/H3) * (H6-Z) ) + 0.16
      IF(Z.GE.(H-H6)) RXH = RX + ( (0.08/H6) * (Z-H) ) - 0.08
C
      RAD = SQRT((RXH*RXH)+(RY*RY))
C
      VC = VE * RAD
      VC = AMIN1(VE,VC)
      VC = VC + ((VE-VC)*(1/H2)*ABS(Z-H2))
C
      IF(RAD.GT. 0.999) GO TO 400
C
      CALCULATE A DEFLECTION ANGLE WITHIN THE STORM.

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C      IF(RXH.LT.0.) WDIV = 90. - (DEGRAD * ATAN(RY/RXH))
C      IF(RXH.GT.0.) WDIV = 270. - (DEGRAD * ATAN(RY/RXH))
C      IF(RXH.EQ.0. .AND. RY.LT.0.) WDIV = 360.
C      IF(RXH.EQ.0. .AND. RY.EQ.0.) WDIV = 999.
C      IF(RXH.EQ.0. .AND. RY.GT.0.) WDIV = 180.

C      IF(WDIV.EQ.999.) GO TO 500

C      WDIF = WDE - WDIV

C      XROT = RAD * COS(WDIF/DEGRAD)
C      YROT = RAD * SIN(WDIF/DEGRAD)

C      SIGN = 0.
C      IF(XROT.GT.0. .AND. YROT.GT.0.) SIGN = +1.
C      IF(XROT.LT.0. .AND. YROT.GT.0.) SIGN = -1.
C      IF(XROT.LT.0. .AND. YROT.LT.0.) SIGN = +1.
C      IF(XROT.GT.0. .AND. YROT.LT.0.) SIGN = -1.

C      BETA = ABS(WDIF)/90.
C      GAMMA = INT(BETA)
C      ANG = (BETA-GAMMA)*90.
C      IF(ANG.GT.45.) ANG = 90. - ANG
C      ANG = ANG * SIGN

C      ANG = ANG * EXP(-RAD*RAD) * (H3/H)*(Z - Z*Z/H)

C      WDC = WDE + ANG
C      IF(WDC.GT.360.) WDC = WDC - 360.
C      IF(WDC.LE.0.) WDC = WDC + 360.
C      GO TO 600

C 400  WDC = WDE
C      GO TO 600

C 500  WDC = 999.

C 600  IF(Z.GT.H6) GO TO 700

C      VG = ( VC + EXP(H6-Z)) * EXP(-PI*RAD)
C      VC = AMAX1(VC,VG)
C      RADDIV = 0.5 * EXP(-Z)
C      IF(RAD.LE.RADDIV) WDC = WDIV

C 700  WS(I,J,K) = VC
C      WD(I,J,K) = WDC

C 300 CONTINUE
C 200 CONTINUE
C 100 CONTINUE

C      CALCULATE THE DROPSIZE DISTRIBUTION AT SELECTED LOCATIONS.
C      DO 800 NL = 1,NLOC

C      XR = ( XDSD(NL) + 1.1) * 10.
C      I = INT(XR)
C      YR = ( YDSD(NL) + 1.1) * 10.
C      J = INT(YR)
C      ZR = ( ZDSD(NL) + 0.5) * 2.
C      K = INT(ZR)

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C
C      RR(NL) = 20.0 * WC(I,J,K)
      ALPHA = 4.1 * (1/RR(NL)**0.21)
C
C      DO 900 ND = 1,21
C          DD(ND) = (ND*0.25) - 0.25
C          DSD(NL,ND) = 8000. * EXP(-ALPHA * DD(ND))
C 900    CONTINUE
C 800 CONTINUE
C      RETURN
      END

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DISTRIBUTION LIST

DEFENSE TECH INFO CENTER 2
CODE DTIC-FD DOC PROC DIV
BLDG 5 CAMERON STATION
ALEXANDRIA VA 22304-6145

COMMANDING OFFICER 12
ATTN CODE 5227 DOCS SEC
NAVRSCHLAB
WASHINGTON DC 20375-5320

COMMANDING OFFICER
ATTN CODE 1221 CLASSIF MGT
NAVRSCHLAB
WASHINGTON DC 20375-5320

NAVRSCHLAB
ATTN CODE 70353
JCSSC MS 39529-5004

COMMANDING OFFICER
CODE 5707 AL DUCKWORTH
NAVRSCHLAB
WASHINGTON DC 20375-5320

COMMANDING OFFICER
CODE 7604 F WIELAND
NAVRSCHLAB
WASHINGTON DC 20375-5320

US NAVAL OBSERVATORY
ATTN OP096 CDR ETRO
34TH & MASSACHUSETTS AVE
WASHINGTON DC 20392-5100

COMNAVAIRSYSCOM
ATTN CODE 526W LCDR WILLIS
WASHINGTON DC 20361-0001

NAVAIRSYSCOM
ATTN PMA 205 1H1 JON SCOTT
WASHINGTON DC 20361-1205

PHILLIPS LABORATORY
ATTN RENE CORMIER PL/GP
HANSCom AFB MA 01731

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WSMR NM 88002-5501

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SAN ANTONIO TX 78228-0510

PARAMAX SYSTEMS CORP
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3880 MURPHY CANYON RD
SAN DIEGO CA 92133